Dark Matter-Neutrino Interactions:
Implications of Solving Small Scale Structure Problems

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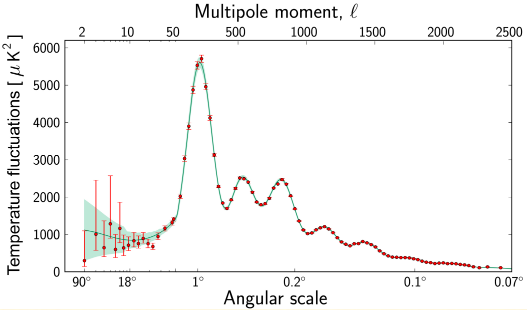
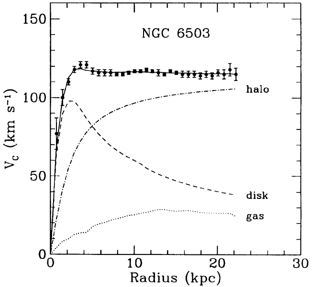
ΛCDM: Very Successful

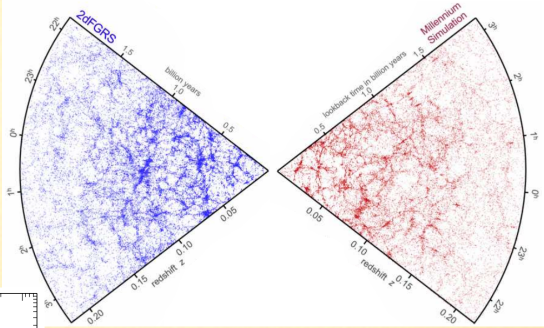


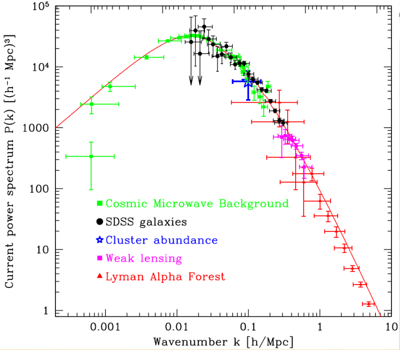


CDM: Success on Large Scales ($\gtrsim$ few Mpc)

Springel et al.,

astro-ph/0604561





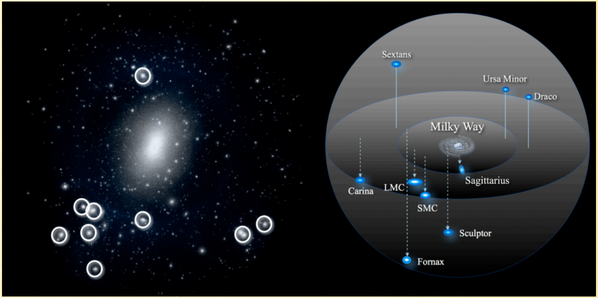
SDSS collaboration,

astro-ph/0310725

CDM: Failure on Small Scales ($\lesssim$ few Mpc)

- Missing satellites

- Too big to fail

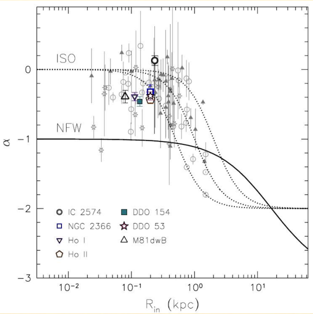


- Core vs. cusp

$$\rho_{NFW}(r) = \frac{\rho_0}{(r/r_c)(1+r/r_c)^2}$$

$$\rho_{ISO}(r) = \frac{\rho_0'}{1+(r/r_c')^2}$$

small r : $\rho \propto r^{\alpha}$



Weinberg et al., 1306.0913; Oh et al., 1011.0899

Possible Solutions

- Better simulations (baryonic physics)
- Warm dark matter
- Self-interacting dark matter
- Neutrino-interacting dark matter

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If neutrino-interacting dark matter is the answer, what does the model look like and what are the implications?

Outline

- Small Scale Structure (Solving the MSP)
- Model Building
- Constraints
- Predictions
- Conclusions

Small Scale Structure

Basic Ideas

- small scale structure forms first $\Longrightarrow$ to erase small scale structure, need $M_{\rm cutoff}$ (smallest mass object formed)
- two scales for washing out structure, one before and one after DM decouples
- relevant decoupling is kinetic not chemical

Chemical Decoupling at $T_{\rm fo}$

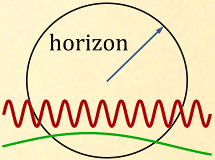
- DM annihilation and creation stops
- co-moving number density of DM becomes constant

Kinetic Decoupling at $T_{\rm d}$

- DM stops interacting with other particles
- after $T_{\rm d}$ DM free-streams
- larger coupling $\Longrightarrow$ smaller $T_{\rm d}$

Small Scale Structure $T > T_{\rm d}$

Acoustic Oscillations



For coupled DM, small scale DM density perturbations will oscillate with the radiation fluid, washing out structure

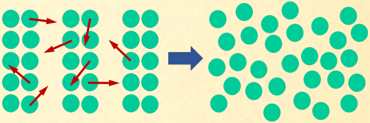
$\Longrightarrow$ damped oscillations on length scales smaller than the horizon size at decoupling, $\left(\frac{1}{H_{\rm d}}\right)$

$$M_{\rm ao} = \rho_\chi(T_{\rm d})\frac{4\pi}{3}\left(\frac{1}{H_{\rm d}}\right)^3 = 2\times 10^8 M_\odot \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{-1/2}\left(\frac{T_{\rm d}}{\rm keV}\right)^{-3}$$

Loeb & Zaldarriaga, astro-ph/0504112

Small Scale Structure $T < T_{\rm d}$

Free Streaming



1. Gravitational potential set up by radiation has decayed
2. DM "warmer" due to neutrino interactions

$\Longrightarrow$ damping on length scales smaller than the distance that DM travels after kinetic decoupling, $\pi a_{\rm eq} \int_{t_{\rm d}}^{t_{\rm eq}} dt (v_{\rm phys}/a(t))$

$$M_{\rm fs} = 7 \times 10^5 M_\odot \left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)^{-1/2} \left(\frac{m_\chi}{10\,{\rm MeV}}\right)^{-3/2} \left(\frac{T_{\rm d}}{\rm keV}\right)^{-3/2} \times \left\{1 + \ln\left[\left(\frac{g_{\rm eff}(T_{\rm d})}{3.36}\right)\left(\frac{T_{\rm d}}{\rm keV}\right)\right]/6.0\right\}^3$$

Green, Hofmann & Schwarz, astro-ph/0503387

Observations of smallest halos

- DM halos around satellite galaxies $\Longrightarrow$ $M_{\rm halo} \sim 10^9 M_\odot$
  (Strigari et al. 0808.3772)
- Lyman-α observations $\Longrightarrow$ $M_{\rm halo} \sim 3 \times 10^8 M_\odot$
  (Viel et al. 1306.2314)
- Gravitational lensing $\Longrightarrow$ $M_{\rm halo} \sim 10^8 M_\odot$
  (Vegetti et al. 1201.3643 & 1405.3666)

We will consider $M_{\rm cutoff} \sim 10^7 - 10^9 M_\odot$ to solve the MSP

- Acoustic oscillations set the cutoff scale
- Need $T_{\rm d} \sim$ keV and large $\chi - \nu$ coupling to achieve this

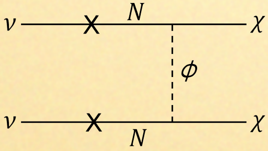
Model Building

Example Model

- Consider a gauge singlet, Weyl DM field χ
- Could couple to neutrinos through the operator $\ell H \chi$, but this would lead to DM decay
- Introduce a dark $U(1)$, a scalar ϕ, and the operator $\frac{1}{\Lambda}\ell H \chi \phi$
- Λ could be due to a sterile neutrino Weyl field N

$$\boxed{-\mathcal{L} \supset MNN + \lambda N H \ell + y \phi N \chi + \text{h.c.}}$$

- See-saw Majorana masses: $m_{\hat{\nu}} \approx \frac{\lambda^2 v^2}{M}$ and $M_{\hat{N}} \approx M$



$$g \approx \frac{\lambda v}{M} y \approx y\sqrt{m_{\hat{\nu}}/M_{\hat{N}}}$$

Example Model (Cont.)

This gives $\sigma_{\chi\nu} \approx \frac{g^4 T^2}{8\pi m_\phi^4}$, $g \approx y\sqrt{m_{\hat{\nu}}/M_{\hat{N}}}$

Solving for T_d:

$$T_\mathrm{d} = 1\ \mathrm{keV} \left(\frac{g_\mathrm{eff}(T_\mathrm{d})}{3.36}\right)^{1/8} \left(\frac{m_\chi}{10\ \mathrm{MeV}}\right)^{1/4} \left(\frac{m_\phi}{20\ \mathrm{MeV}}\right) \left(\frac{|g|}{0.3}\right)^{-1}$$

So solving the MSP $\implies g \gtrsim 0.1 \implies M_{\hat{N}} \lesssim 10\ \mathrm{eV}$

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So solving the MSP $\Longrightarrow$ $g \gtrsim 0.1$ $\Longrightarrow$ $M_{\hat{N}} \lesssim 10$ eV

✗ Doesn't work! (N_eff, BBN, …)

Viable Model

- Abandon simple neutrino masses (no LNV in the DM/N sector)
- Add two sterile Weyl fields: N_1 and N_2 (with opposite lepton number)

$$\boxed{-\mathcal{L} \supset m_{ij}\nu_i\nu_j + MN_1N_2 + \lambda_i N_1 H \ell_i + y_1\phi^* N_1 \chi + y_2 \phi N_2 \chi + \text{h.c.}}$$

$$\text{Mass matrix:} \quad \begin{pmatrix} m_{ij} & \lambda_j v & 0 \\ \lambda_i v & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

- Majorana masses $m_{\hat{\nu}_i} \approx m_i$ and Dirac mass $M_{\hat{N}} \approx M$
- Still have $g_i \approx \frac{\lambda_i v}{M} y_2$ but it's no longer related to $m_{\hat{\nu}_i}$

Viable Model (Cont.)

- Mass basis: 3 light Majorana neutrinos $\hat{\nu}_i$, heavy (~ 100 MeV) Dirac neutrino $\hat{N}$

$$\hat{N} = \begin{pmatrix} \hat{\nu}_4 \\ N_1^* \end{pmatrix}$$

- In principle, $\hat{\nu}_4$ can consist of any arbitrary combination of sterile (N_2) and active flavors

$$\hat{\nu}_4 = U^*_{\ell 4} \nu_\ell \quad \text{where } U \text{ is the } 4 \times 4 \text{ mixing matrix}$$

$\chi \to N_2 \to \hat{\nu}_4 \to \nu_e,\ \nu_\mu,\ \nu_\tau,$ so want $|U_{\ell 4}|$ large for large coupling

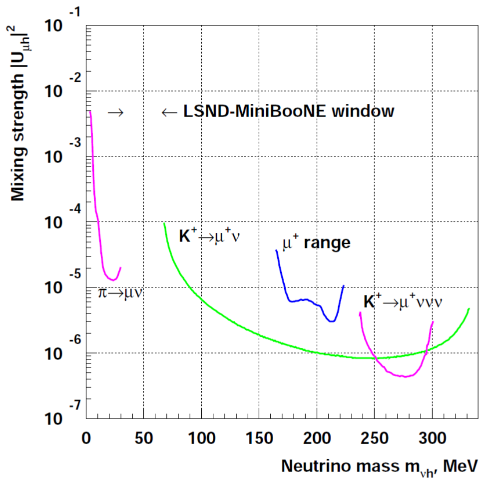
Constraints

Electroweak Constraints

U_{e4} and $U_{\mu 4}$ are strongly constrained from line searches in muon and meson decays and electroweak precision measurements

The heavy $\hat{\nu}_4$ part of ν_μ or ν_e alters decay rates ($\hat{\nu}_4$ decays invisibly)

$$\boxed{|U_{e4}|^2, |U_{\mu 4}|^2 \lesssim 10^{-4} - 10^{-5}}$$



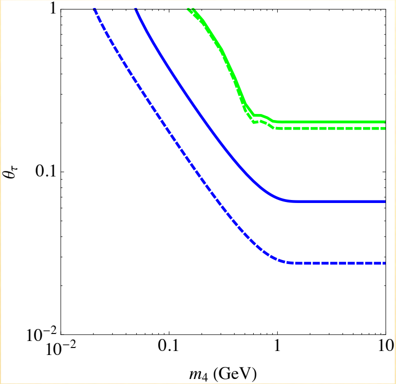
Gninenko, 1009.5536

need strong coupling to solve MSP $\Rightarrow$ $\boxed{\text{only consider } \hat{\nu}_4 \text{ part of } \nu_\tau}$

τ Decays

- τ decay rates and the energy distribution of the decay products are altered

- Only consider adding $\hat{\nu}_4$ to $\nu_\tau \implies$ one new parameter θ_τ
- $\nu_\tau = c_{\theta_\tau} \sum_{i=1}^{3} V_{\tau i}\hat{\nu}_i + s_{\theta_\tau}\hat{\nu}_4$, $\quad |U_{\tau 4}|^2 = s^2_{\theta_\tau}$



green: $\tau \to \nu 3\pi$

blue: $\tau \to \ell\nu\bar{\nu}$

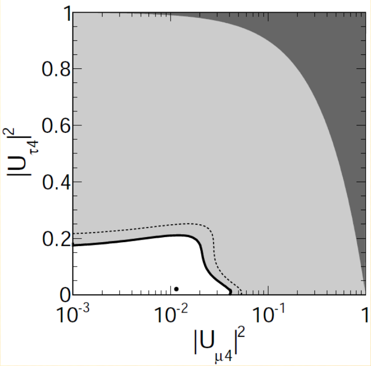
- - - 68% C.L.
—— 95% C.L.

Neutrino Oscillation Experiments

- Can measure 3-neutrino mixing parameters independently from sterile parameters

- SuperK (no matter effects) measures $\mu \to$ sterile: $\boxed{\theta_\tau \lesssim 0.42}$ (limited by data)

- Solar NCs: $\boxed{\theta_\tau \lesssim 0.6}$ (poorly understood Φ_B)



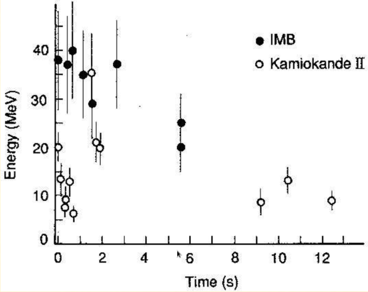
Abe et al., 1410.2008

- Presence of sterile neutrino alters oscillations in matter over a distance scale $\sim$ 4000 km—LBNF (1300 km), NOνA (810 km)

Strumia & Vissani, hep-ph/0606054; Cirelli et al., hep-ph/0403158

Supernova 1987A

- Usually light DM ($m_\chi \lesssim 100$ MeV) is constrained by supernova energy loss



- Neutrino-interacting DM needs $m_\chi = \mathcal{O}(10)$ MeV to solve the MSP

- Similar to Fayet et al., hep-ph/0602169: $m_\chi \gtrsim 10$ MeV

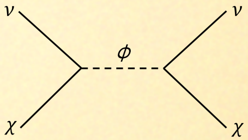
We plan to study the effects on neutrino spectra in detail in future work

Predictions

Supernova Neutrino Observations

- Supernova release most of their energy in $\sim 10^{58}$ neutrinos

- Neutrinos can resonantly scatter off DM and out of the line of sight of our detectors



- Model this using standard neutrino oscillations plus a decay term

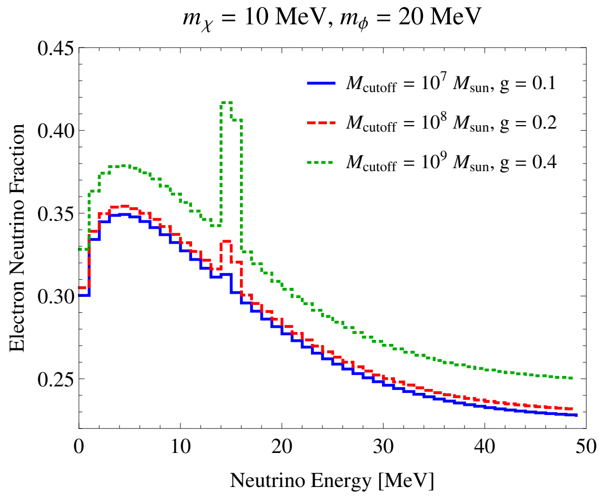
$$\boxed{H + i\frac{\Gamma}{2}}$$

- Neutrino oscillations $\implies$ each $\hat{\nu}_i$ has its own decay probability

$$\boxed{\approx \; |U_{Ni}|^2 \int_{\text{l.o.s.}} dx \, n_\chi(x) \sigma_{\chi N}}$$

Supernova Neutrinos (SN 1987A)

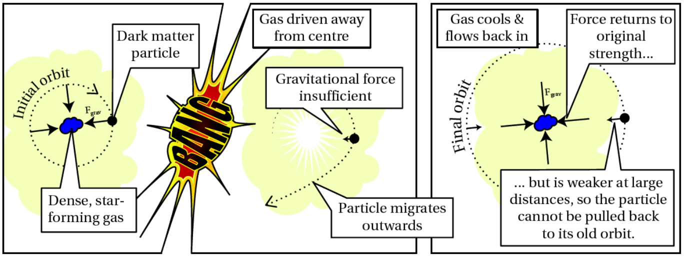
Ignoring changes in neutrino spectra for now...



$$\nu_e \text{ fraction} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} \qquad E_{\text{res}} = \frac{m_\phi^2 - m_\chi^2}{2m_\chi}$$

More Small Scale Structure Problems

The cusp-core and the too big to fail problems could be alleviated by "feedback" due to supernova or reionized gas



Pontzen & Governato, 1402.1764

- In simulations $\sim 0.1 - 1\%$ of SN energy gets transferred to DM
- Neutrino-interacting DM could get supernova energy directly

Using DM-neutrino scattering, $\approx 0.1\%$ of SN energy will be transferred to DM over 1 kpc

Conclusions

- Gravity-only simulations of ΛCDM fail on sub-galaxy scales
- Neutrino-interacting DM is viable and could alleviate these small scale structure problems
- This implies observable features in astrophysical neutrino spectra and motivates studying τ decays, neutrino oscillations, and supernova neutrinos

Backup Slides

Kinetic Decoupling

Estimate T_d for χ-ν scattering:

- non-relativistic DM and relativistic νs

$$\Longrightarrow \; \Delta p \sim p_\nu \sim T$$

- change in p_χ after N collisions is $\mathcal{O}(1)$ when

$$\Delta p_{\rm tot} \sim \sqrt{N} T = p_\chi \sim \sqrt{m_\chi T}$$
$$\Longrightarrow \; N \sim m_\chi / T \gg 1$$

- Kinetic decoupling occurs when

$$\boxed{N\tau = \tfrac{m_\chi}{T} \left(n_\nu \sigma_{\chi\nu} v\right)^{-1} \sim H^{-1}}$$

What about future supernovae?

- Rate of core-collapse supernova is a few per century in a Milky Way sized galaxy
- Most likely distance ~ 10 kpc
- Current detectors will see $\sim 10^2 - 10^4$ events at this distance

For a supernova ~ 10 kpc away, with $M_{\rm cutoff} = 10^9 M_\odot$, this neutrino-DM resonance is observable.